ジェットを”持たない”銀河からの高エネルギーガンマ線放射

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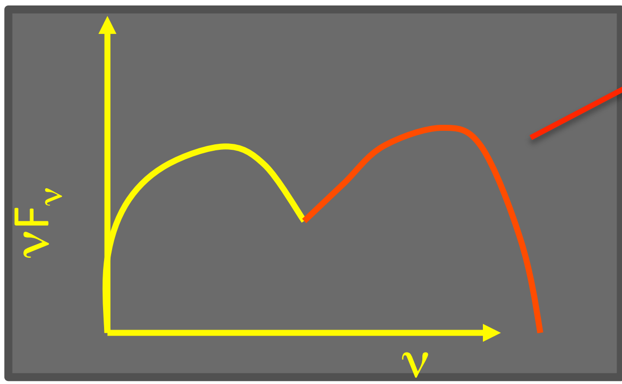
2014年10月2日

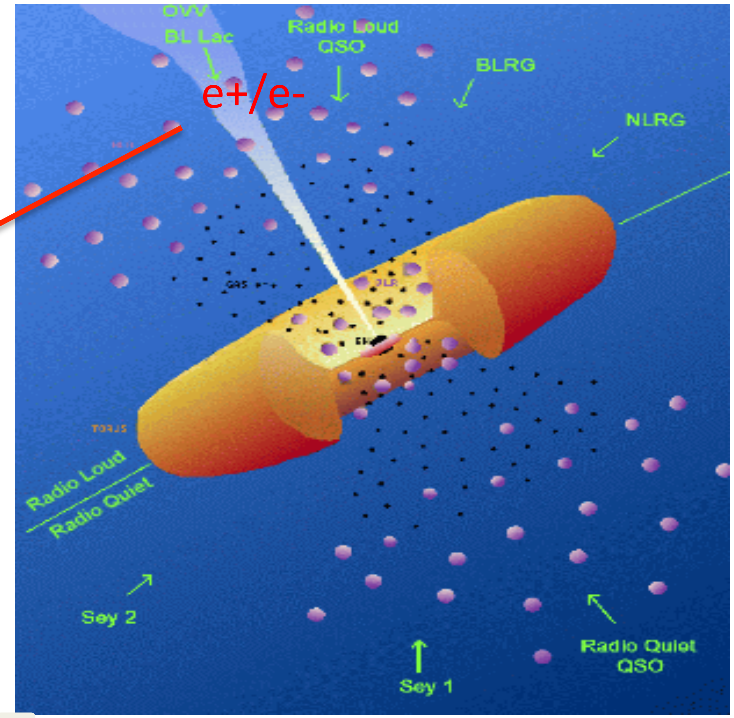
「高エネルギーガンマ線でみる極限宇宙2014」
＠東大柏キャンパス

Gamma-ray emission from galaxies

AGNs with relativistic jet

Inverse-Compton scattering
by electrons in the jets



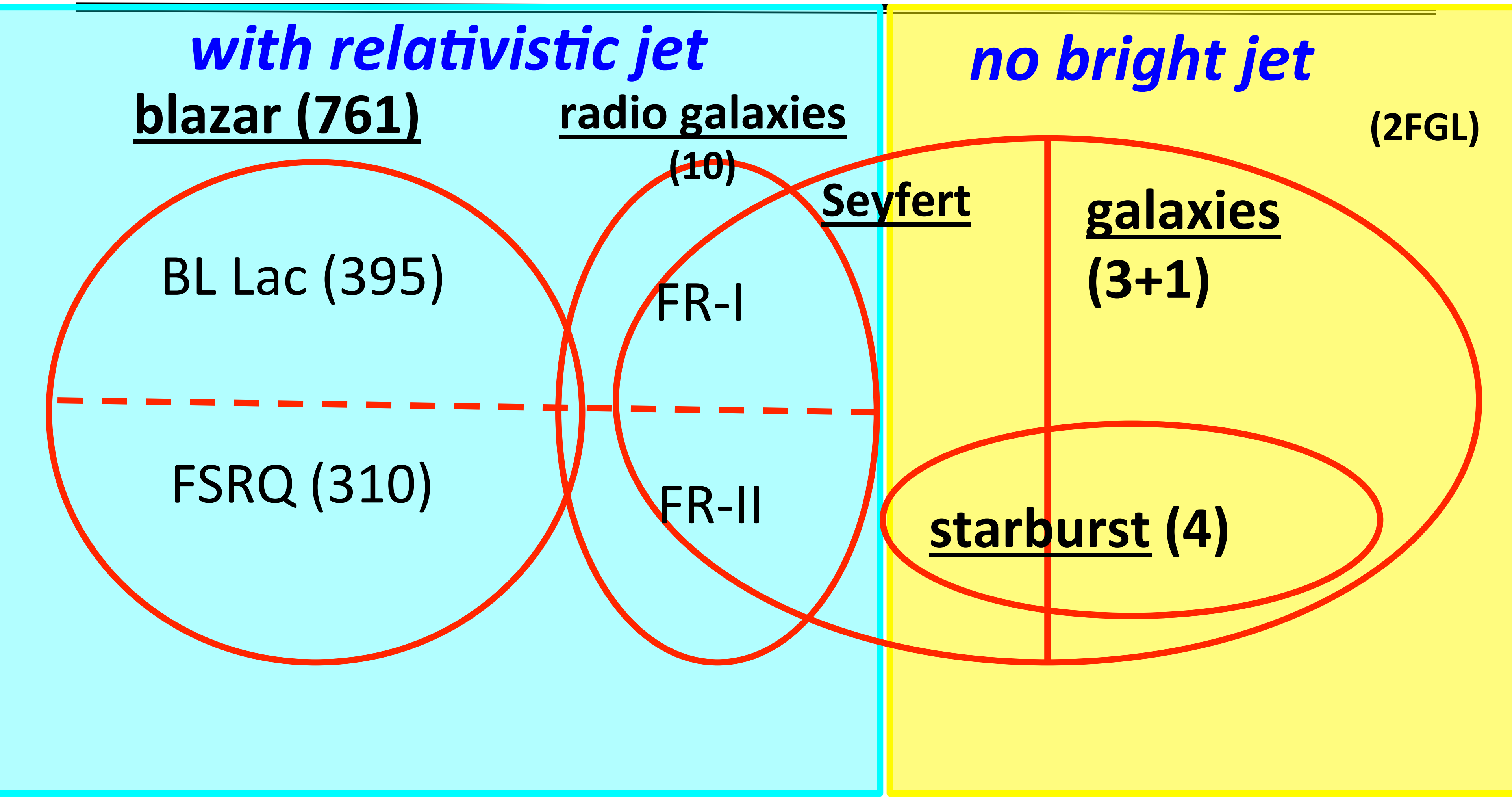


	Blazar	Radio Galaxies
• low power	BL Lac	FR I
• high power	FSRQ	FR II
	small viewing angle -> relativistic beaming	mis-aligned blazar ?

no relativistic jet

(Seyferts, starbrust, galaxies)

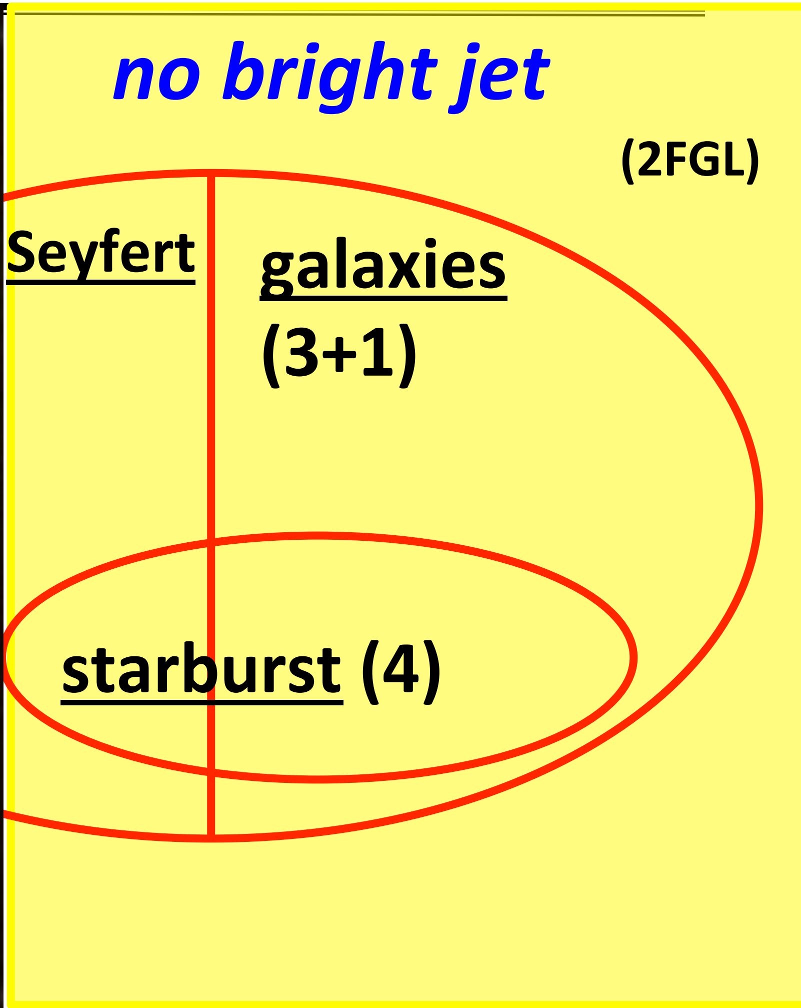
extra-galactic γ-ray sources



radio loud

radio quiet

extra-galactic γ-ray sources



radio loud

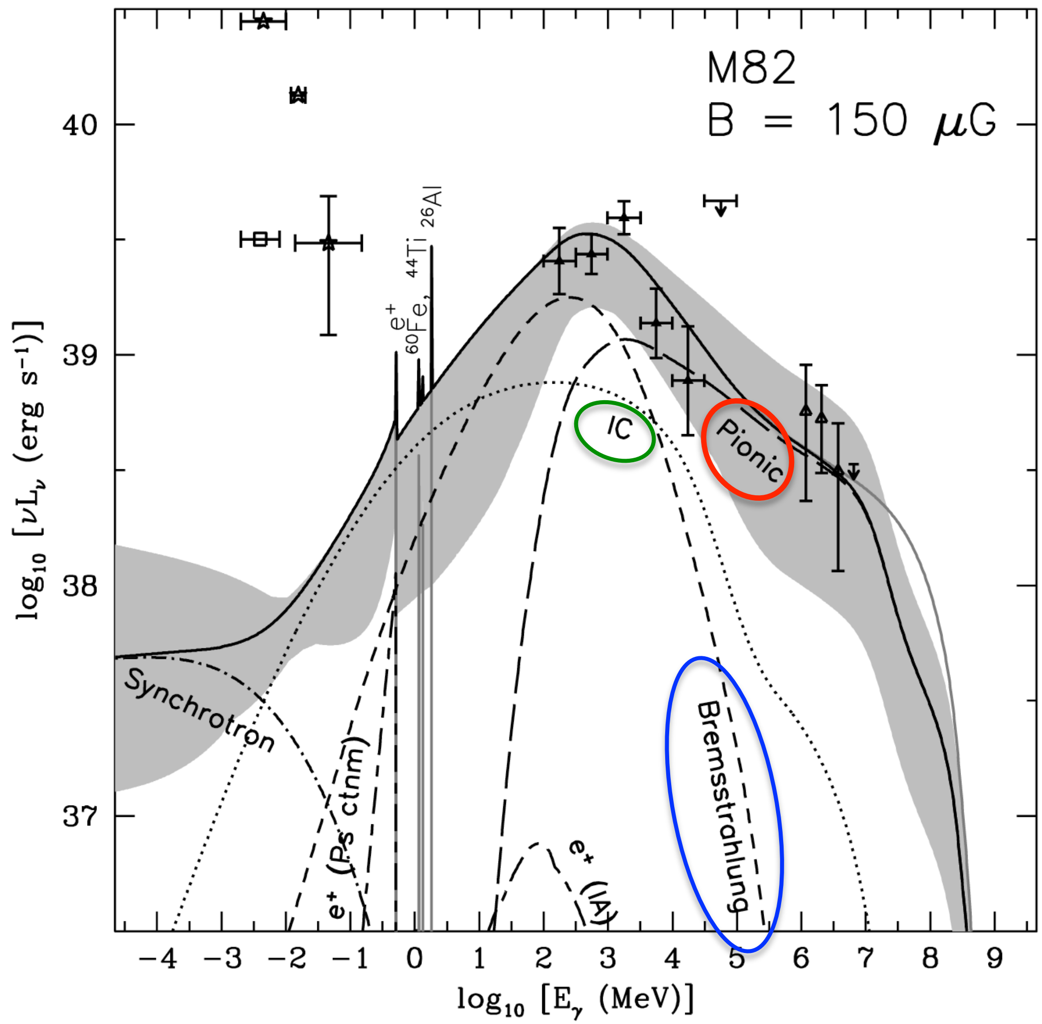
radio quiet

starburst galaxies

an example of emission model (Lacki+14, ApJ)

emission origins in the HE (>100 MeV) γ-ray band are

- Bremsstrahlung
- inverse-Compton
- Pionic ($\pi^0 \rightarrow \gamma\gamma$)



nucleus activity in radio-quiet galaxies

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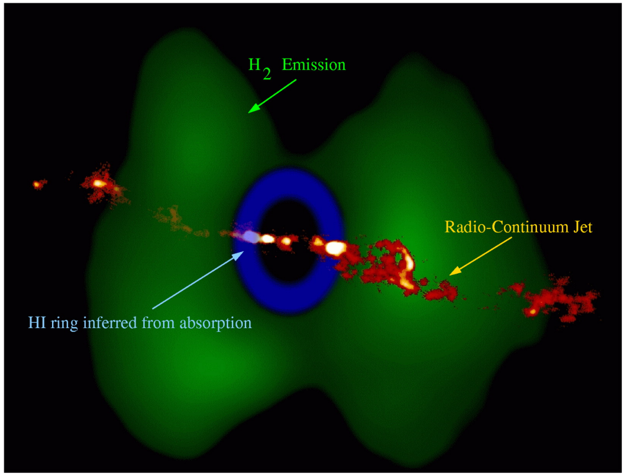
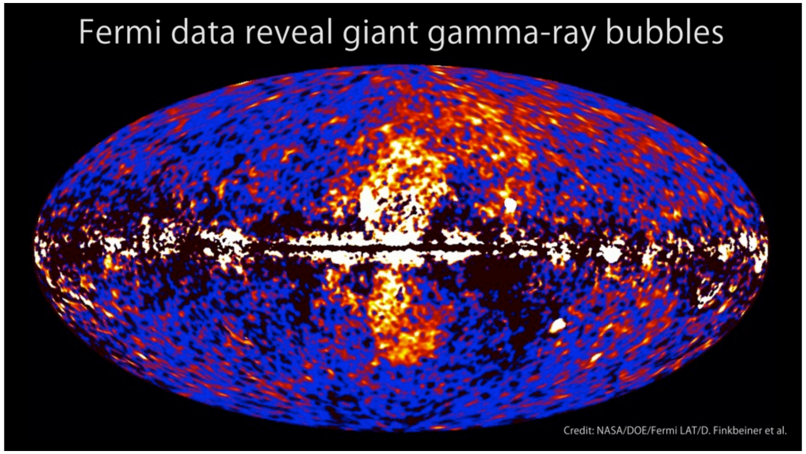
"radio quiet" does not mean 'radio silent'!!



"jet" (non-relativistic) in Seyfert

240-pc jet in NGC 4151(Sy1.5) is two-sided and highly collimated
(diameter < 1.4 pc, v < 0.03c at 0.1-10pc scale)



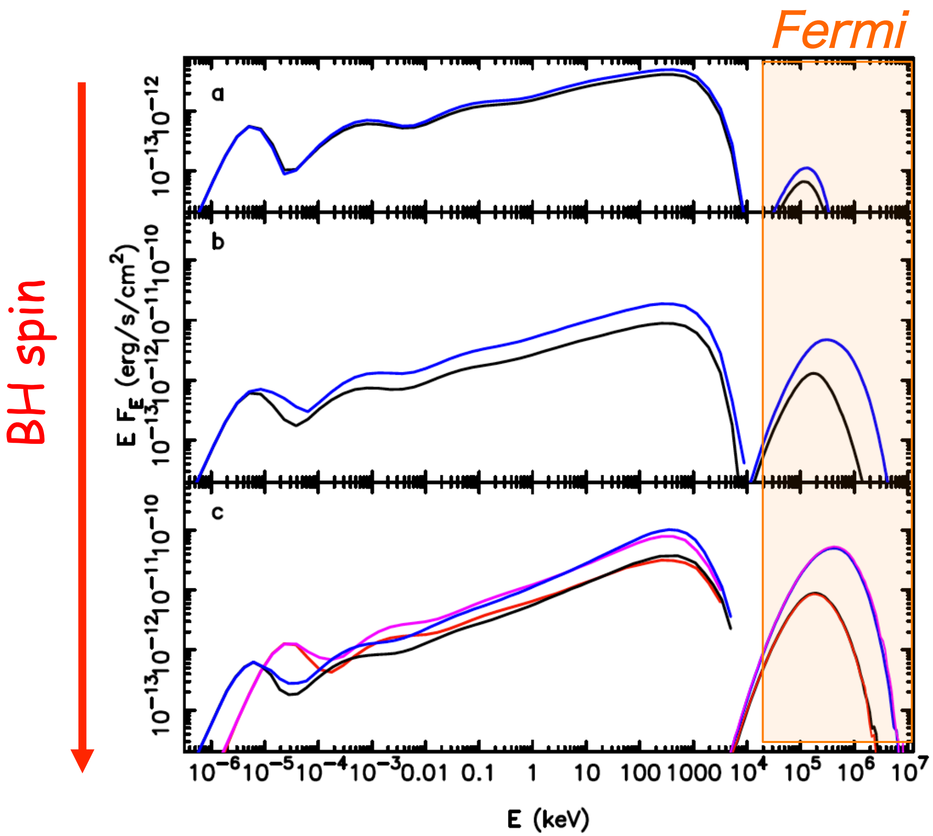
extended "lobe" (a few-10 kpc)

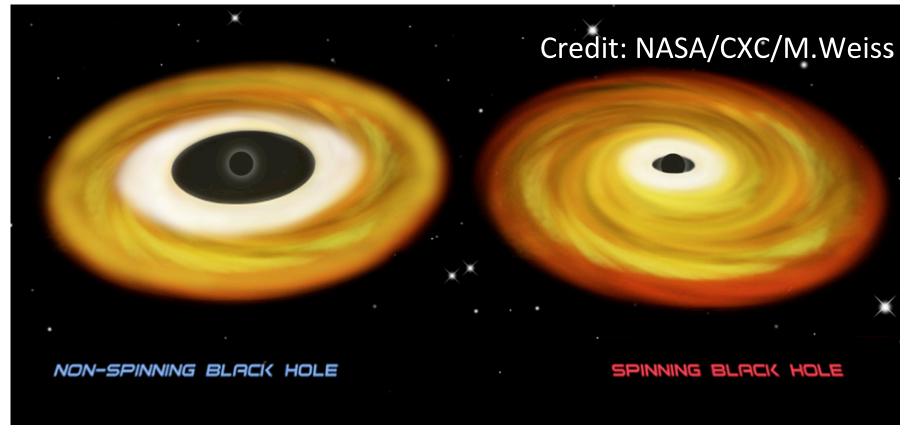
Fermi bubble in our Galaxy!
（明日、佐々木さん）

+Ultra Fast Outflow (UFO) (井上Sさん)

hadronic process in the disk

p-p interactions in the innermost parts of the accretion disk
if L < $10^{-3}L_{Edd}$(明日、木村さん？)





First idea was discussed for Galactic black hole systems
(Mahadeven et al.1997:
Oka & Manmoto 2003),
and then, applied to AGN by
Niedzwiecki+13 ApJ

Source samples

(Fermi-LAT 2012 ApJ, 755)

- **IR galaxies:** 64 low-redshift ($z < 0.06$) galaxies based on HCN Survey (Gao & Solomon 2004)

(star-formation activity evidenced by dense molecular gas)

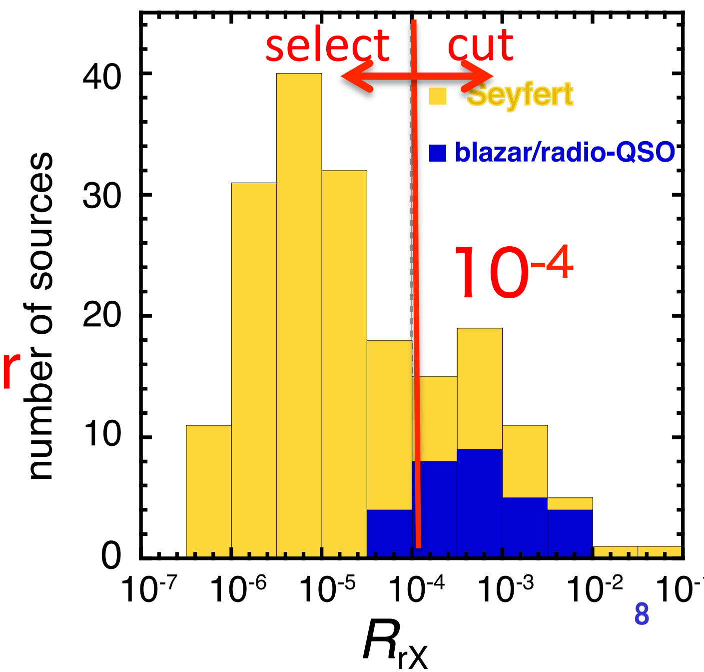
+ 5 local galaxies

(Fermi-LAT 2012 ApJ, 747, CA:MH)

- **Radio-quiet Seyfert galaxies:** 120 sources based on Swift-BAT 58 month catalog

hard X-ray radio loudness parameter

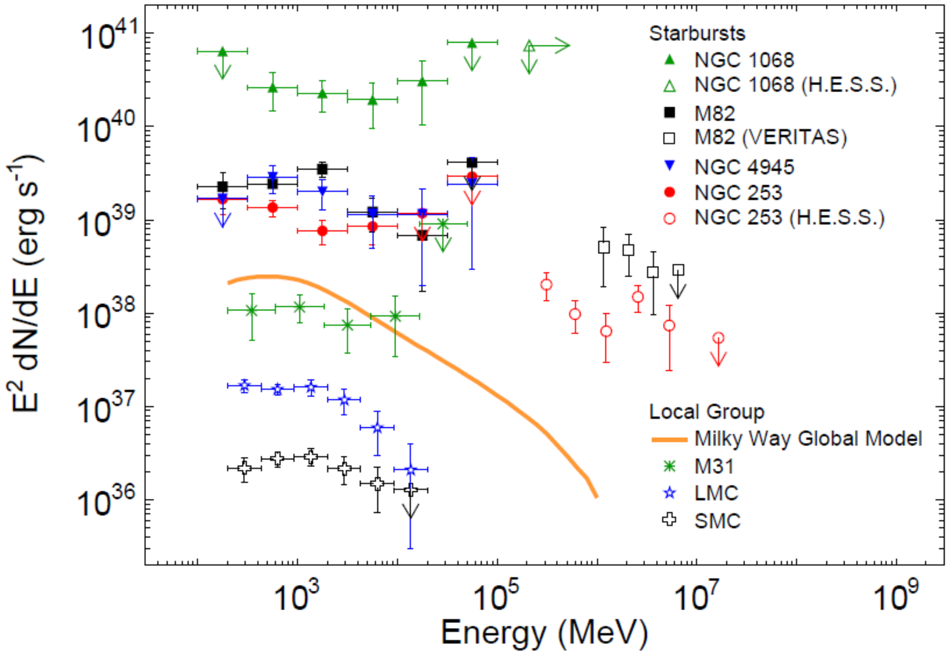
$$R_{\rm rX} = \frac{[\nu F_\nu]_{1.4\,{\rm GHz}}}{F_{14-195\,{\rm keV}}}$$

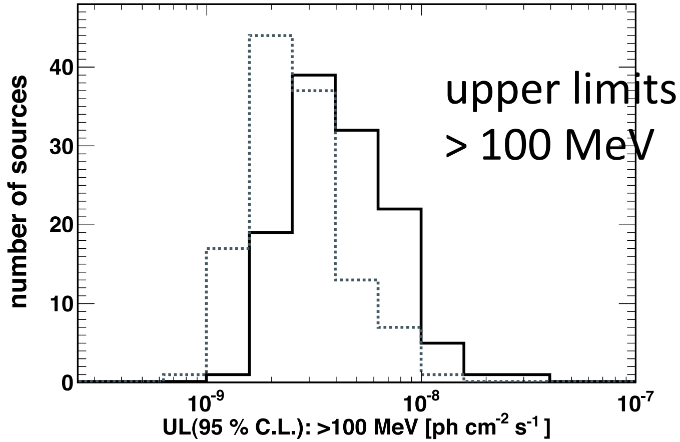


Analysis results

Data: 3-years Fermi-LAT data above 100 MeV

- 7 LAT detections:
  SMC, LMC, M31,
  M82, NGC 253,
  NGC 4945, NGC 1068
  (2 TeV detections:
  M82, NGC 253)
- No detection in radio-quiet Seyferts





The mean ULs (>100 MeV) :
$\sim 4\times10^{-9}$ ph cm^{-2} s^{-1}

possible detections?
ESO 323-G077, NGC 6814

Global Emissions

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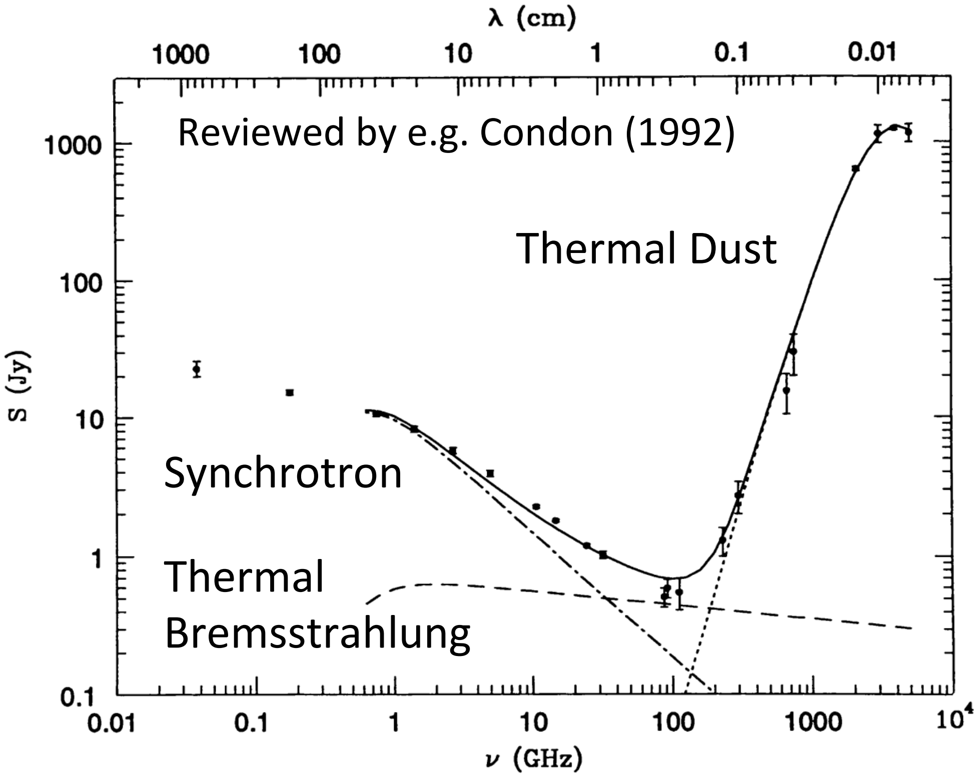
Radio and Far-IR SED for M82



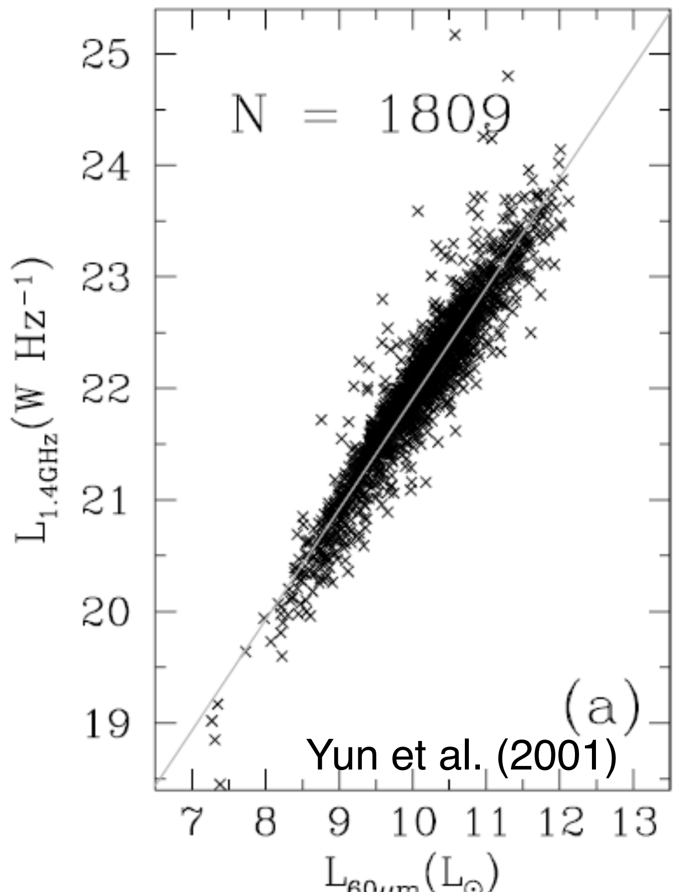
$$\mathrm{SFR}(M_\odot\,\mathrm{yr}^{-1}) = 1.7 \times 10^{-10} L_{8-1000\mu\mathrm{m}}(L_\odot).$$

(Kennicutt 1998)

$$\mathrm{SFR}(M_\odot\,\mathrm{yr}^{-1}) = (5.9 \pm 1.8) \times 10^{-22} L_{1.4\mathrm{GHz}}, (\mathrm{W\,Hz}^{-1}).$$

(Yun et al. 2001)

Empirical Radio Far-IR Correlation



Luminosity Scaling Relations

Ackermann et al. 2012, ApJ, 755, 164

$$\mathrm{SFR}(M_\odot\,\mathrm{yr}^{-1}) = 1.7 \times 10^{-10} L_{8-1000\mu\mathrm{m}}(L_\odot).$$

(Kennicutt 1998)

Gamma-ray vs. IR Luminosity

Power law slope = 1.17 ± 0.07

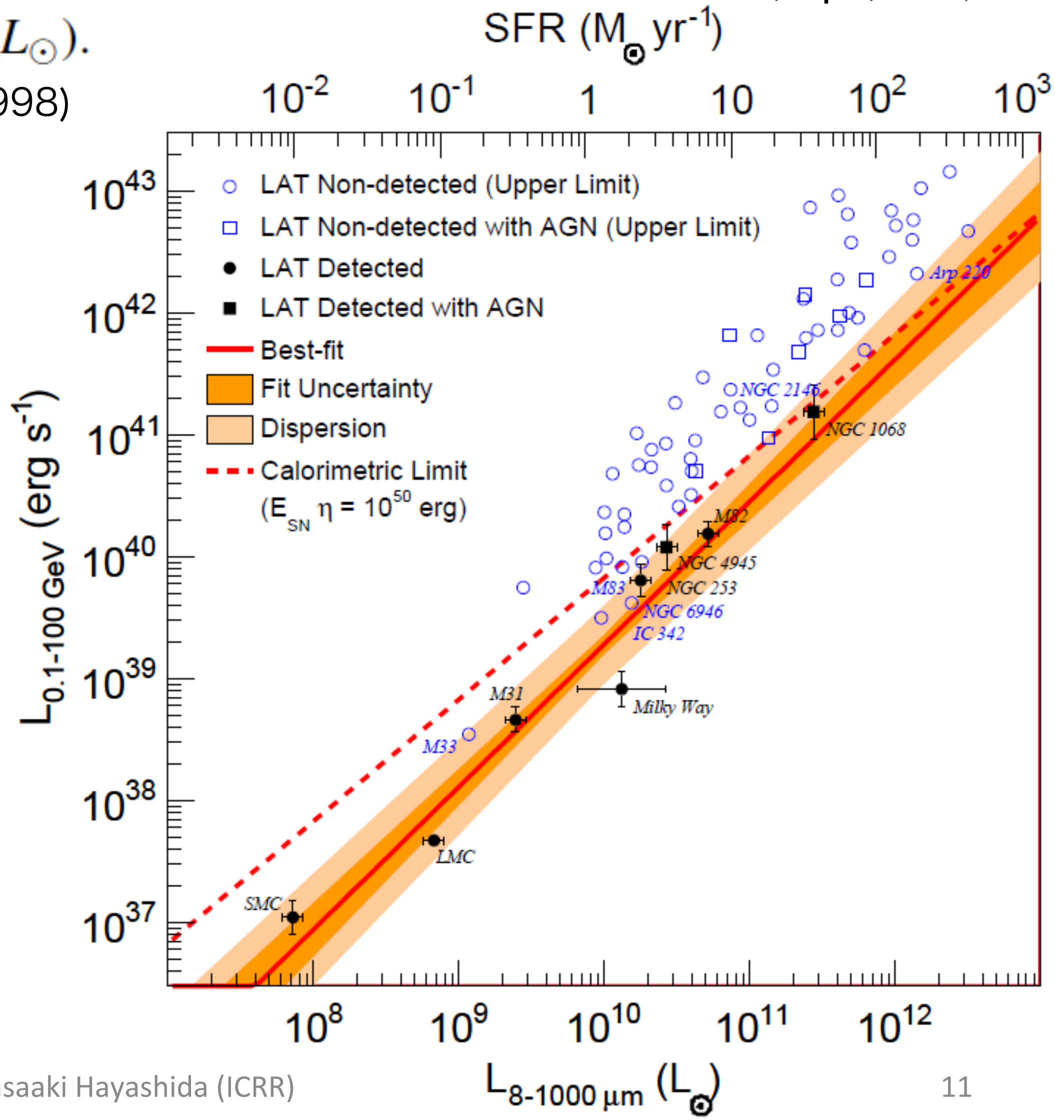
Sqrt(variance) = 0.24

Upper limits included in fit

Correlation significance accounting for selection effects and distance uncertainties

P < 0.005

(*P* < 0.02 excluding galaxies hosting *Swift* -BAT AGN)



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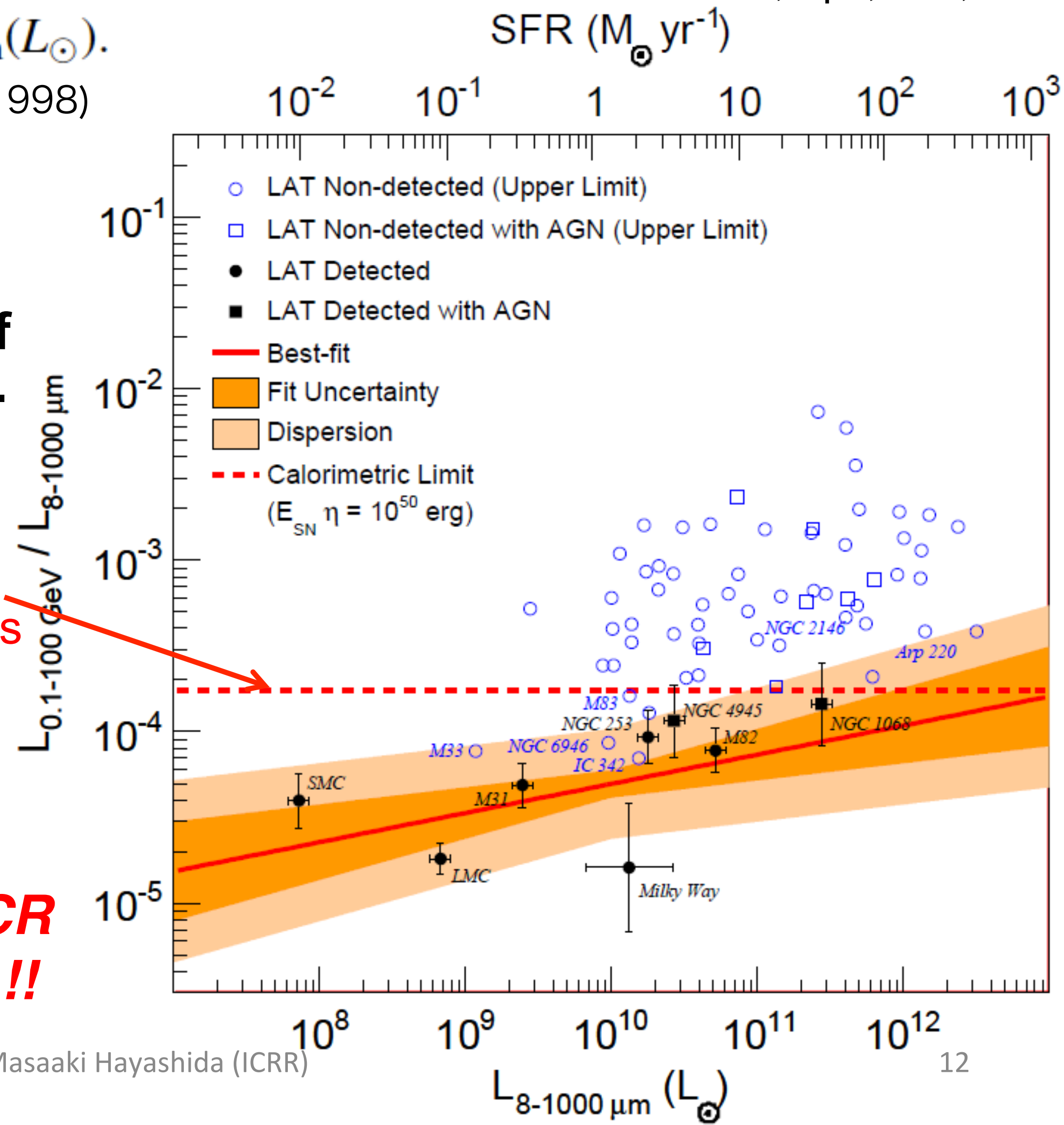


Gamma-ray vs. IR Luminosity

Luminosity ratio is measure of gamma-ray yield per unit star-formation

In "calorimetric limit", inelastic collisions dominate CR energy losses (here, assume each SNR injects 10^{50} erg of CR nuclei)

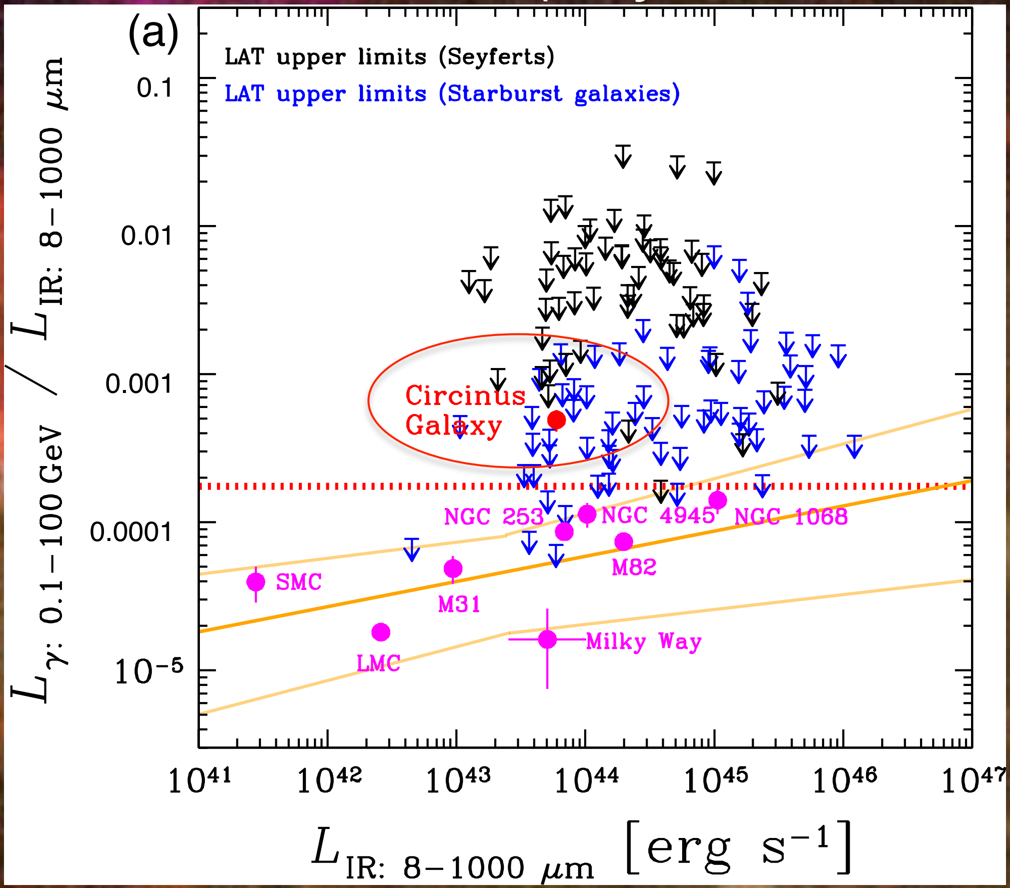
(most probably)

gamma rays originate from CR in (all) star-forming galaxies !!

However,,

However,,

(Hayashida+13, ApJ)



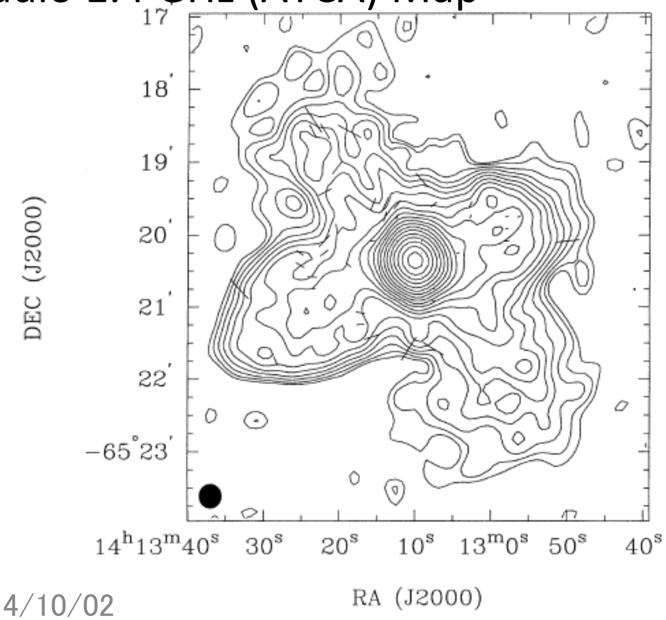
one exception!!

gamma-ray flux is higher than flux expected from Calorimetric limits

Circinus galaxy

- (RA, Dec: J2000) = ($14^h13^m09.95^s$, $-65^d20'21.2''$) (southern source)
- Distance: 4.2 Mpc (Tully et al. 2009)
- Black hole mass $(1.7\pm0.3)\times10^6 M_{sun}$ (Greenhill et al. 2003), also known as a starburst galaxy and Seyfert 2 type AGN.
- kpc-scale radio lobes, as well as jet-like structure (e.g., M. Elmouttie et al. 1998)

Radio 1.4 GHz (ATCA) Map



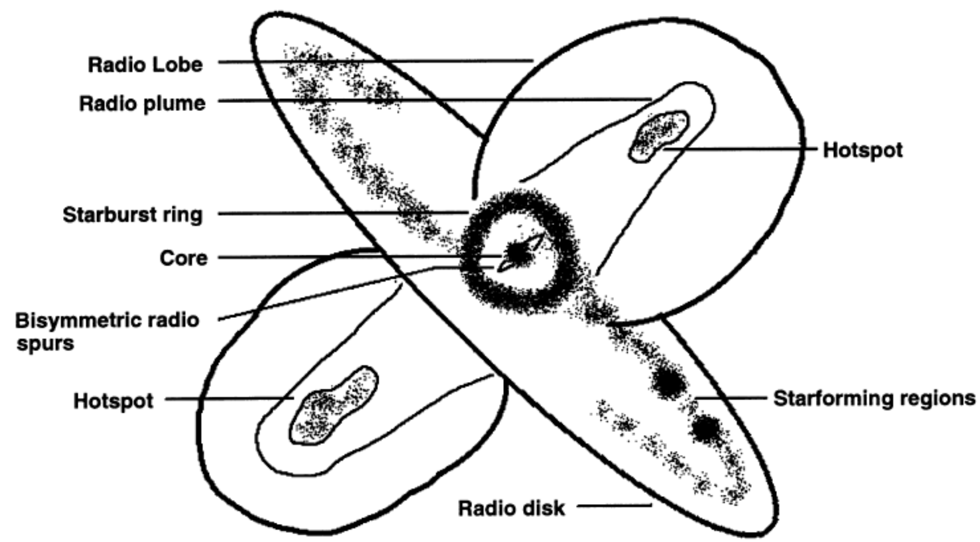
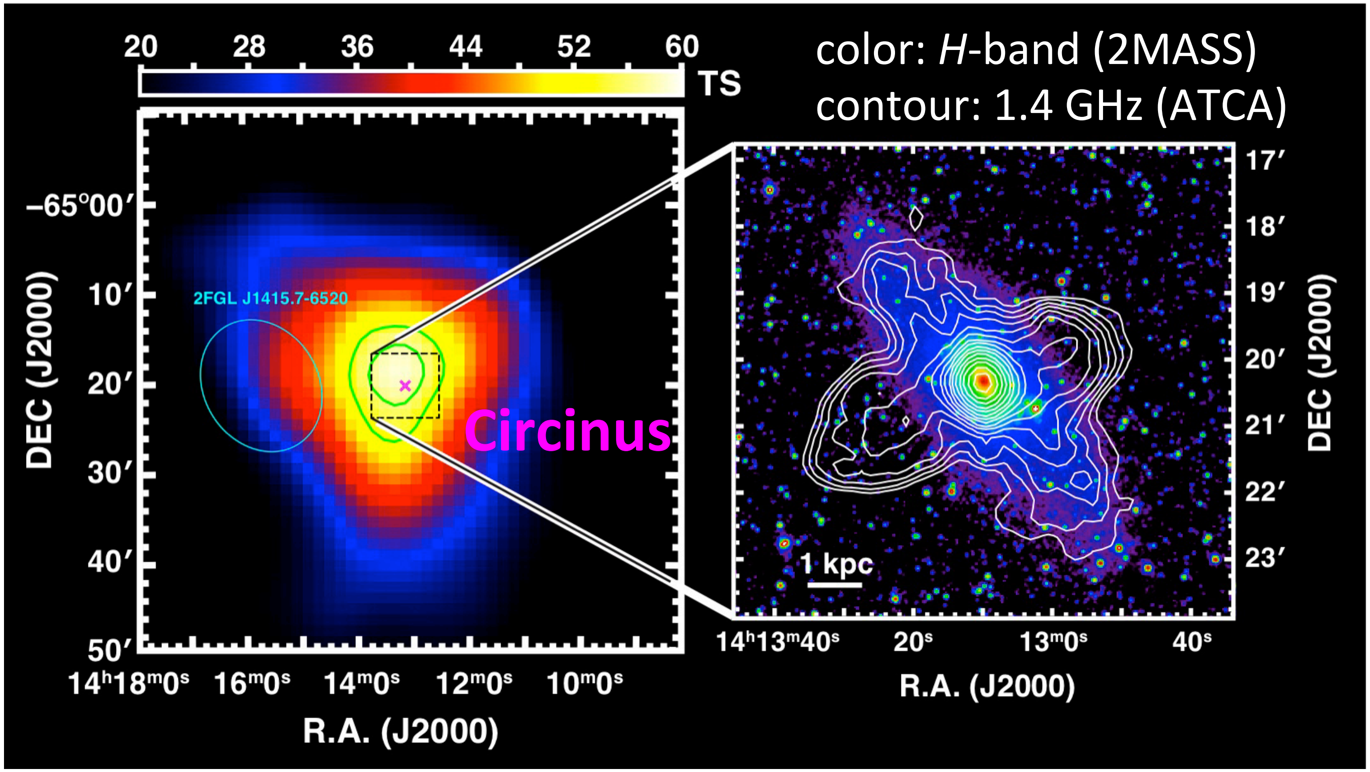


Figure 13. The proposed geometry for the radio continuum structures in Circinus. The figure is not to scale.

GeV γ-ray TS map with a radio/IR map

(Hayashida+13,ApJ)

4-year observation by Fermi-LAT



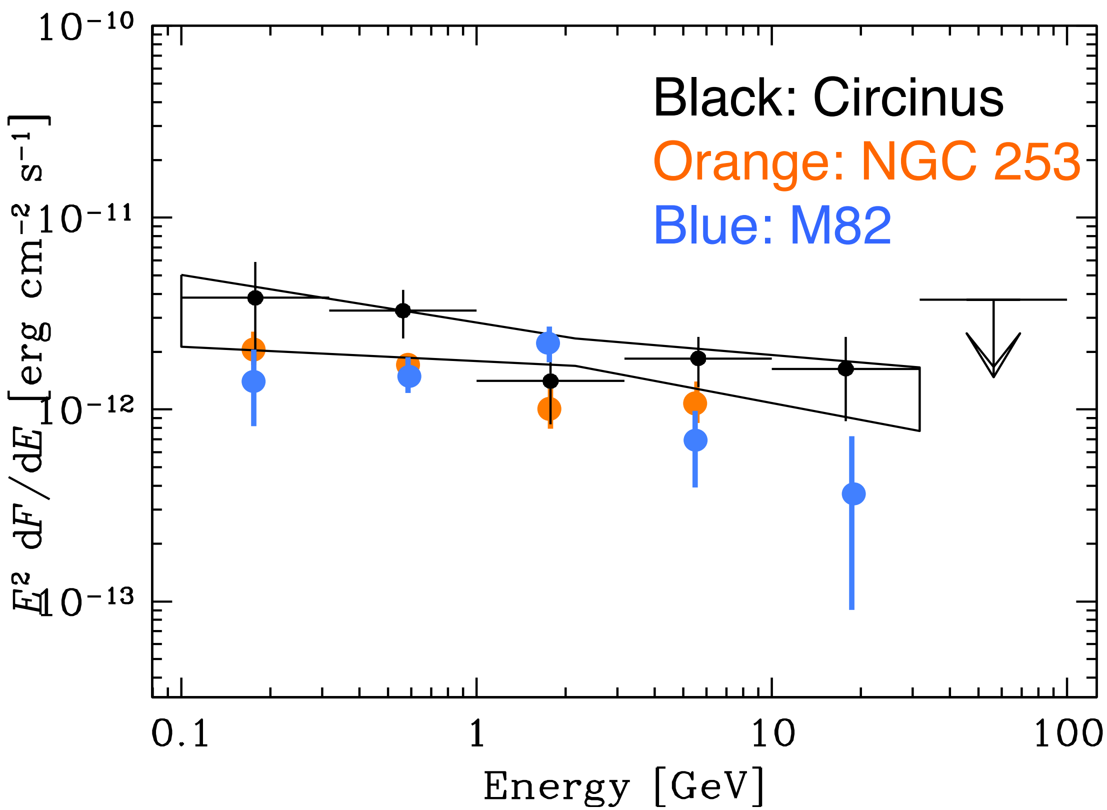
Circinis is well located inside of LAT 68 % CL region.

TS: 58 (~7 σ), a single point-like source

Gamma-ray spectrum

(Hayashida+13,ApJ)

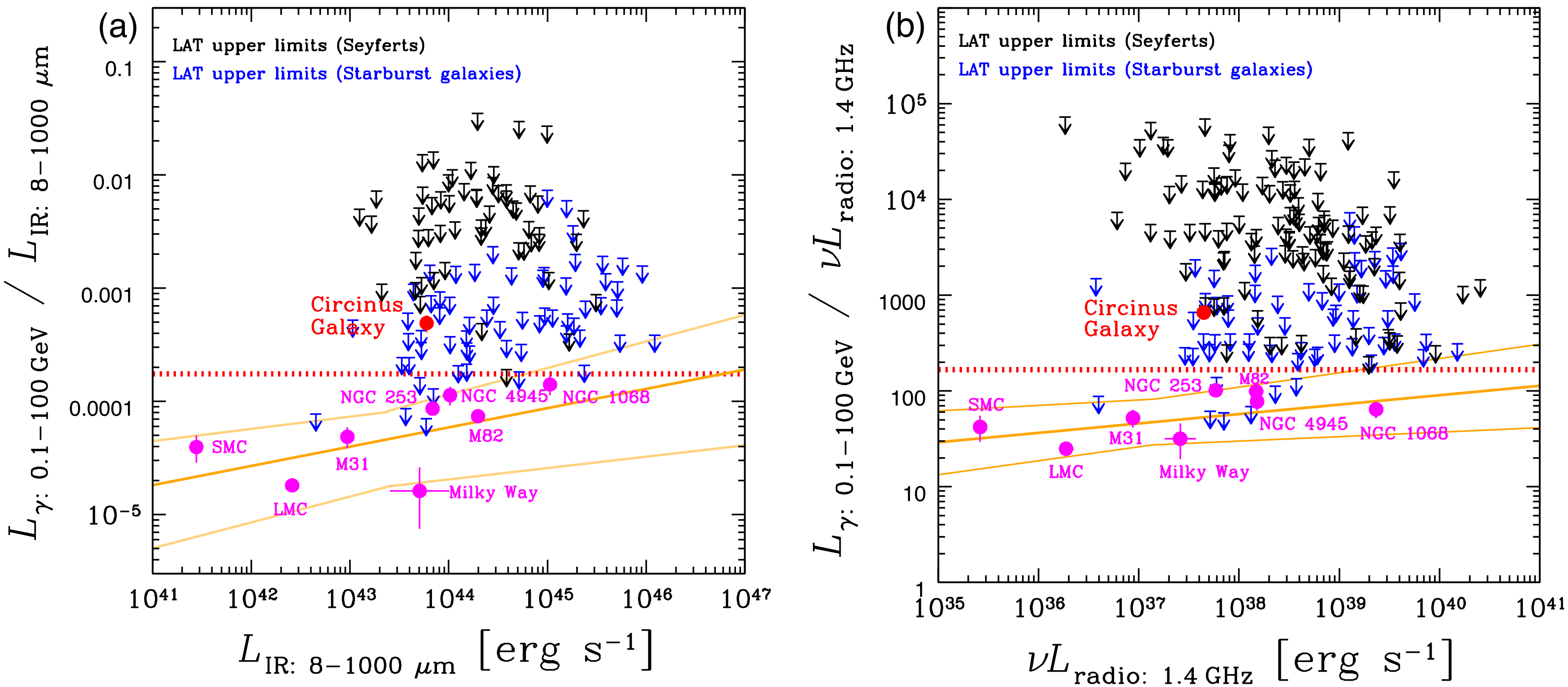
- **Simple power law, Index: 2.19±0.12**
- Flux (> 100MeV): (1.88±0.58)x10^{-8} ph cm^{-2} s^{-1}



- No indication of curved spectral shape
- No significant variability

Comparison in the γ-ray and IR/radio

(Hayashida+13,ApJ)

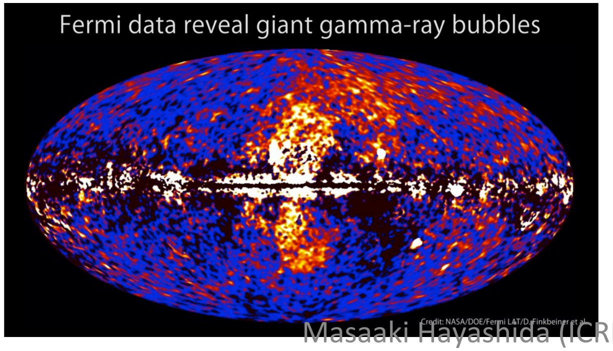


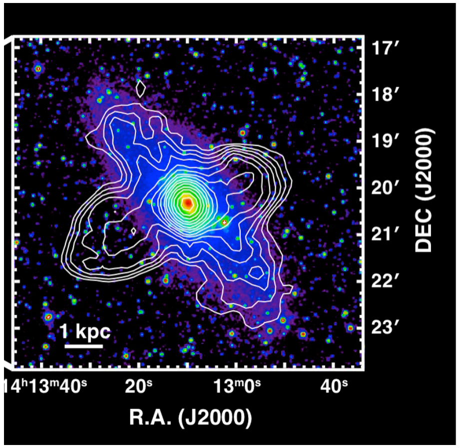
- Circinus Galaxy shows higher $L\gamma/L_{IR}$ and in $L\gamma/L_{radio}$ ratios
- higher than the calorimetric limit (with 10% efficiency)

calorimetric limit when $\eta E_{SN}=10^{50}$ erg

Origin of γ ray emission?

- relativistic jets? -> no radio result shows a pronounced nuclear jet activity
- Disk? (including hadronic process)
  → our Seyfert study revealed such emission should be less than a few % of X-ray luminosity
  → not sufficient to account for the excess
- Lobes? (see next slides)





Radio images and flux

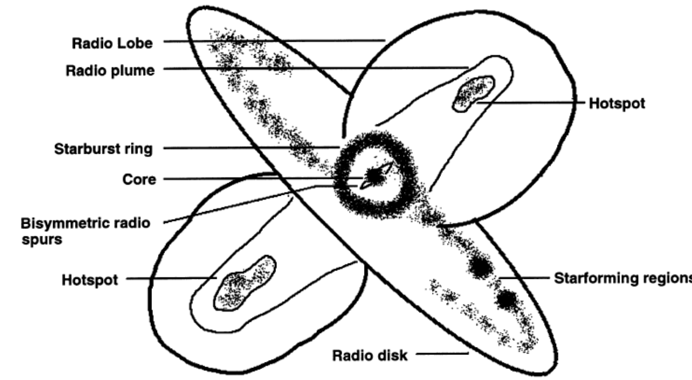


Figure 13. The proposed geometry for the radio continuum structures in Circinus. The figure is not to scale.

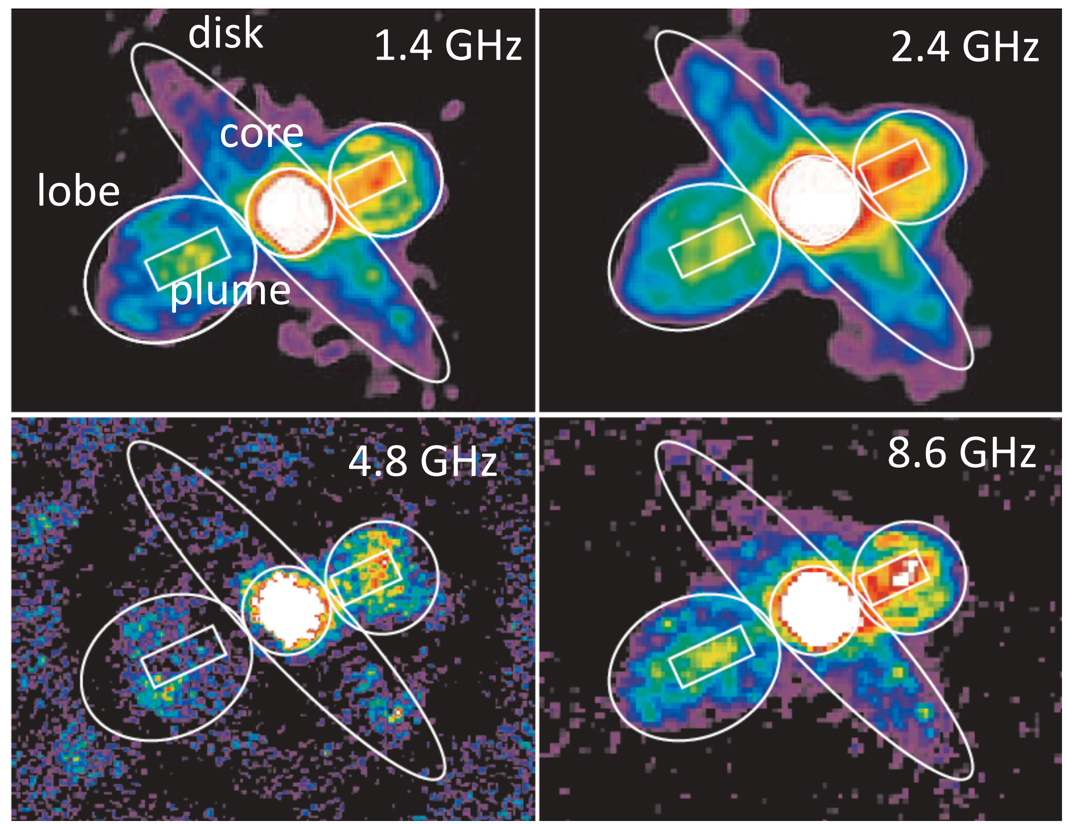
We extract radio fluxes from each region in accordance with Elmouttie et al. 1998

Definition of components:

<lobe> :SE: ellipse with r=70",55"
NW: circle r=44.6"

<core> : circle r=35"

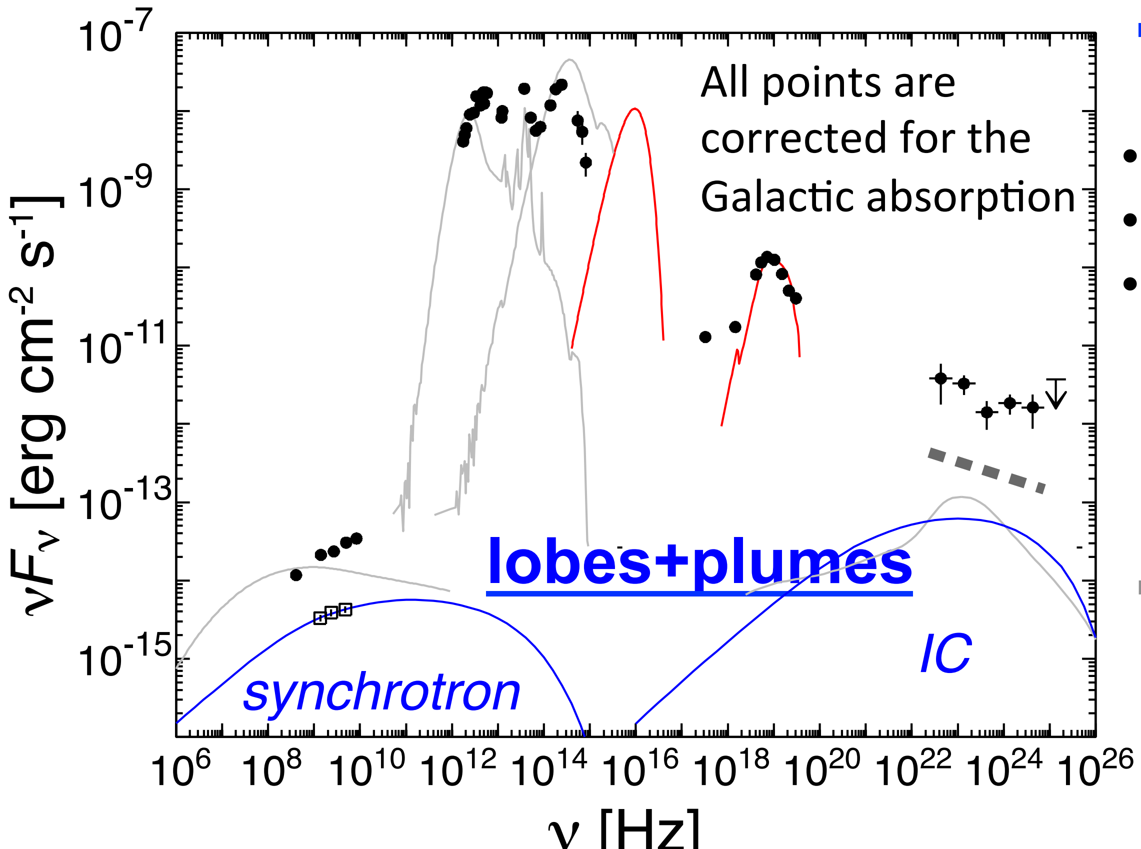
lobes+plumes contribute to ~10 % level of the total radio flux



(ATCA data provided by M. Elmouttie)

Broad-band SED

Black circle: total fluxes of the galaxy



emission model for the lobes + plumes

- B = 5-10 μG
- equipartition (u_e/u_B=1)
- seed photons
  - CMB
  - FIR-to-optical
  - UV-to-hard X-ray

γ-ray spectrum expected from γ-IR relation in starbursts

Lobe can hardly account for the observed GeV emission
(unless very far from the equipartition)

the origin is not clear, yet,,,,

CTA case for Circinus galaxy

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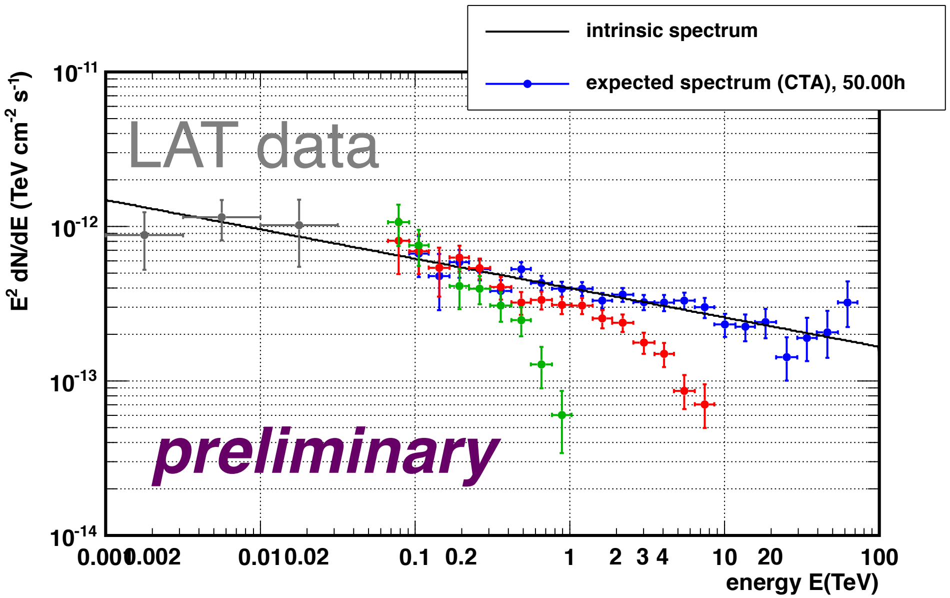
- 50 hours observations

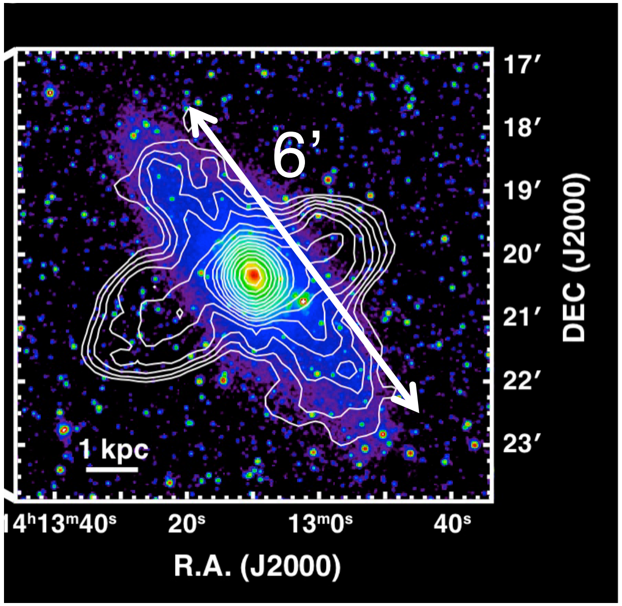


Blue: simple power low

Red: × exp(–E/5TeV)

Green: × exp(–E/0.5 TeV)

can clearly detect cut offs!

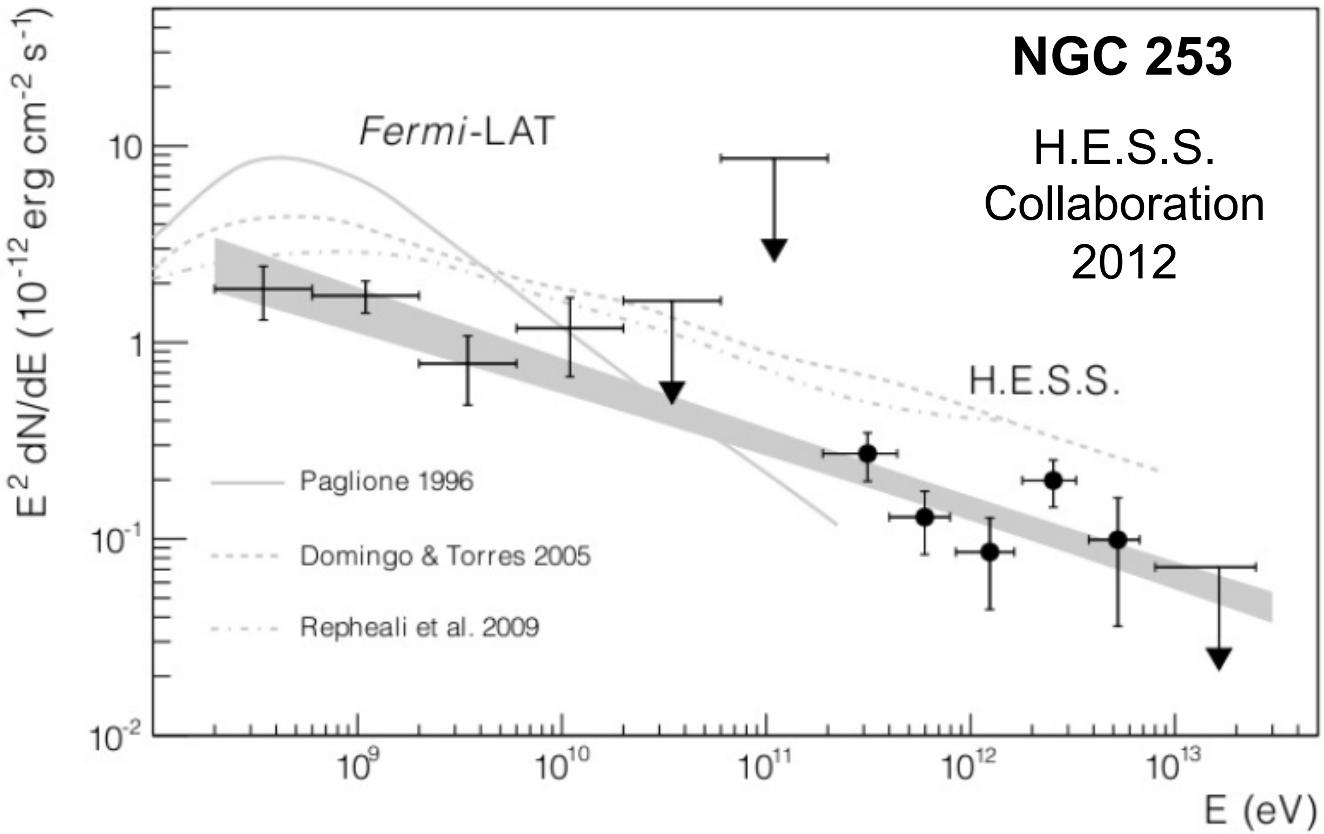


can resolve disk and lobe!!

GeV-TeV spectra in starbursts

Currently,,,,

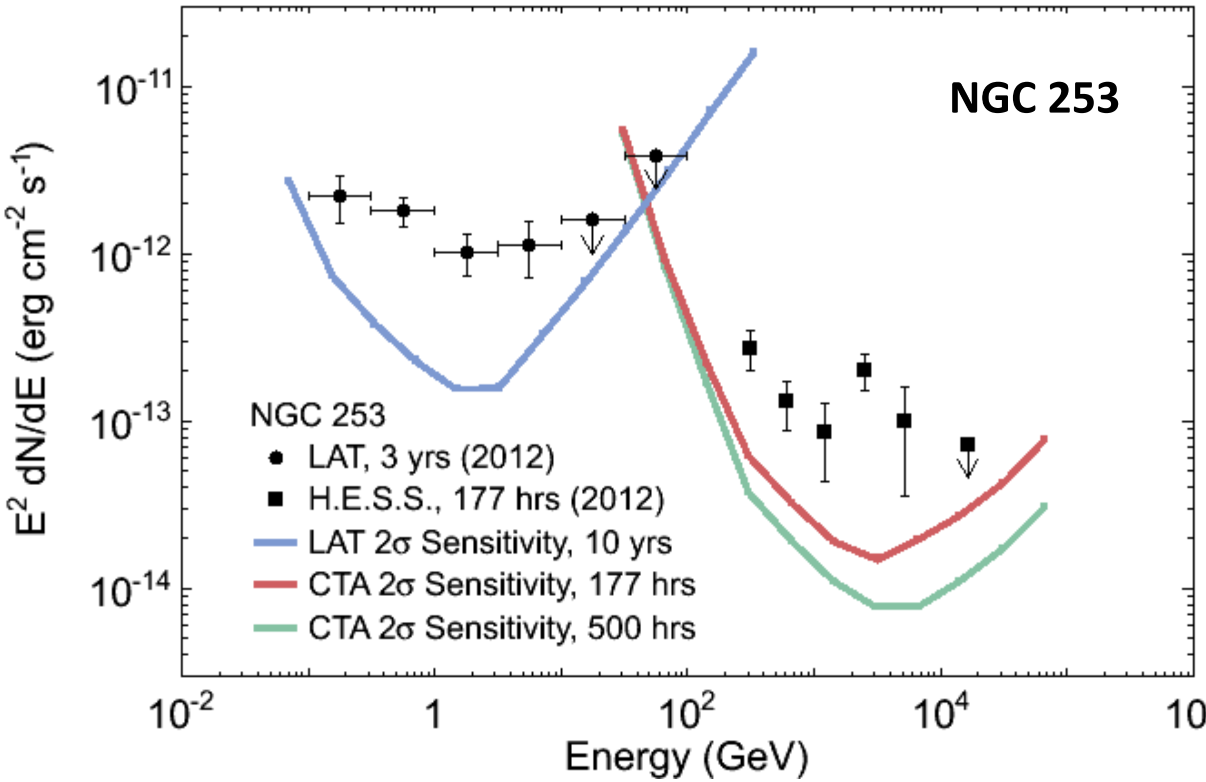
Gamma-ray spectra of M82 and NGC 253 are well described by simple power laws given current statistical precision



CTA Science Opportunities

Gamma-ray detections of NGC 253 with future differential sensitivity curves overlaid

defined as 2σ detections in bins of 1/3 decade in energy (courtesy Stefan Funk, Keith Bechtol see also arXiv:1205.0832)



Example CTA Research Areas

- Are γ-ray spectra of starbursts more complex than simple power laws?
- Highest energy CRs in starburst systems?
- Can the starburst / disk be separated with CTA imaging?

CTA Science Opportunities

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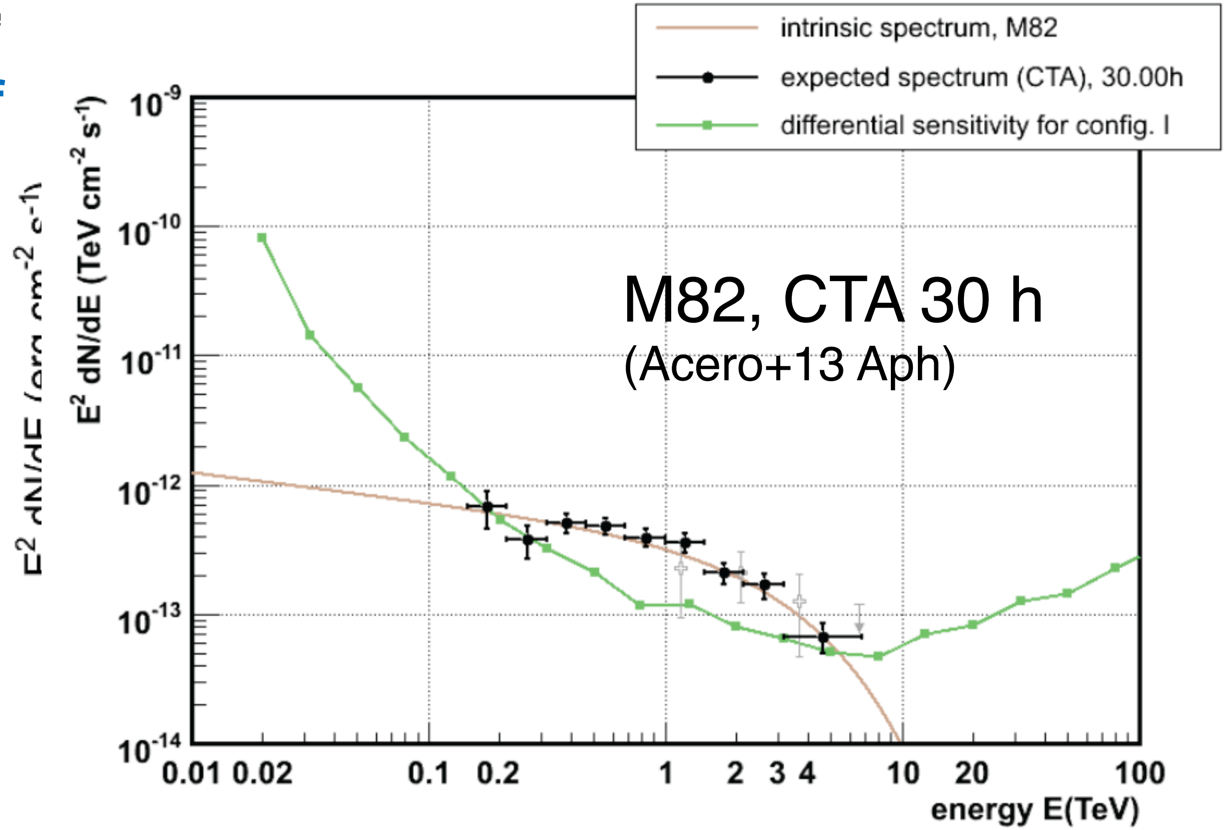

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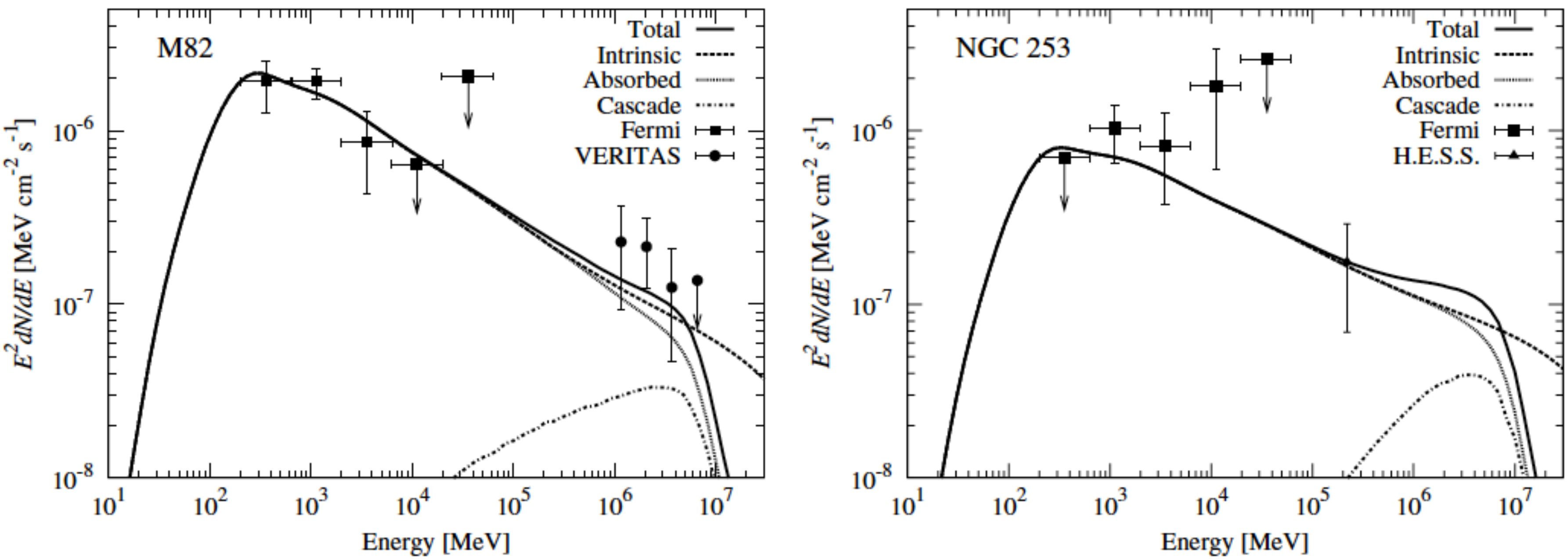
Cascade emission in galaxies

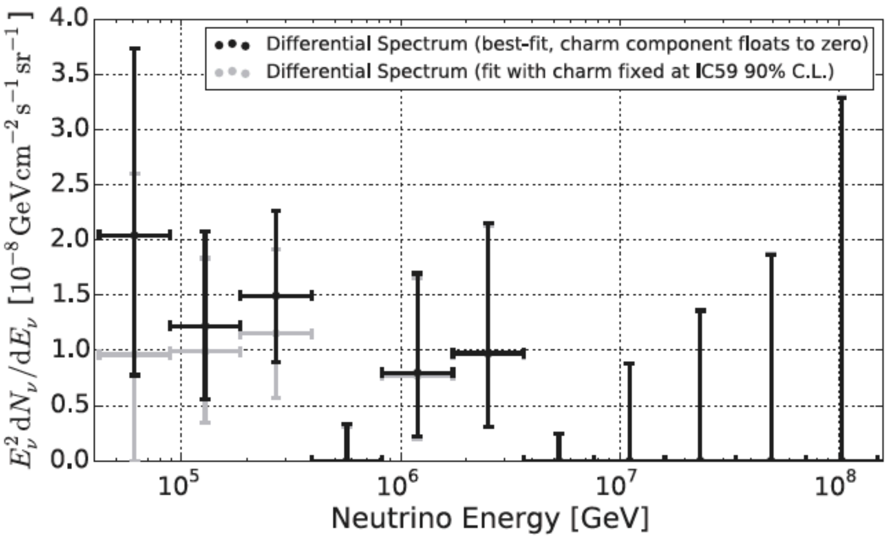
Y .Inoue 2011, ApJ

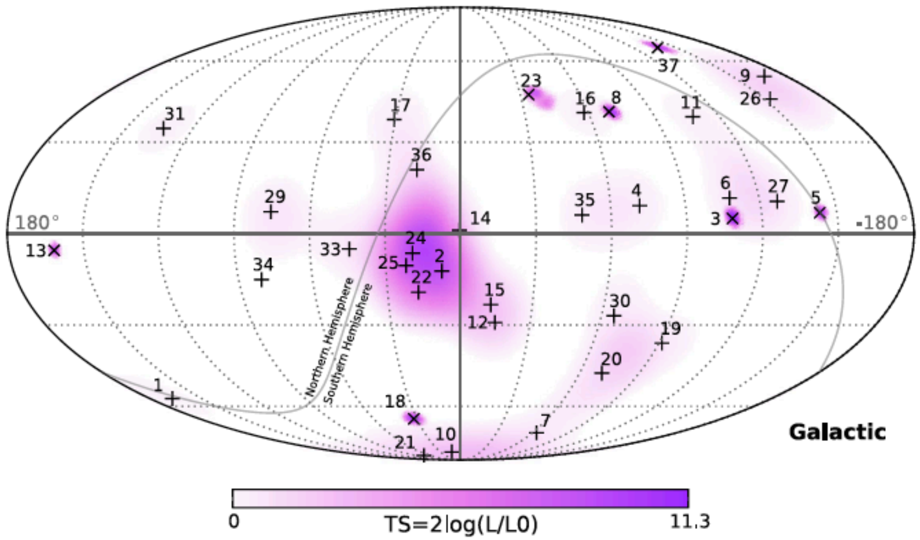


HE gamma-ray (above 10 TeV) can not escape from galaxies

HE Astrophysical Neutrinos

(IceCube coll.14, PRL: 詳細は明日の石原さん)





37 events: flux: $E^2\Phi \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

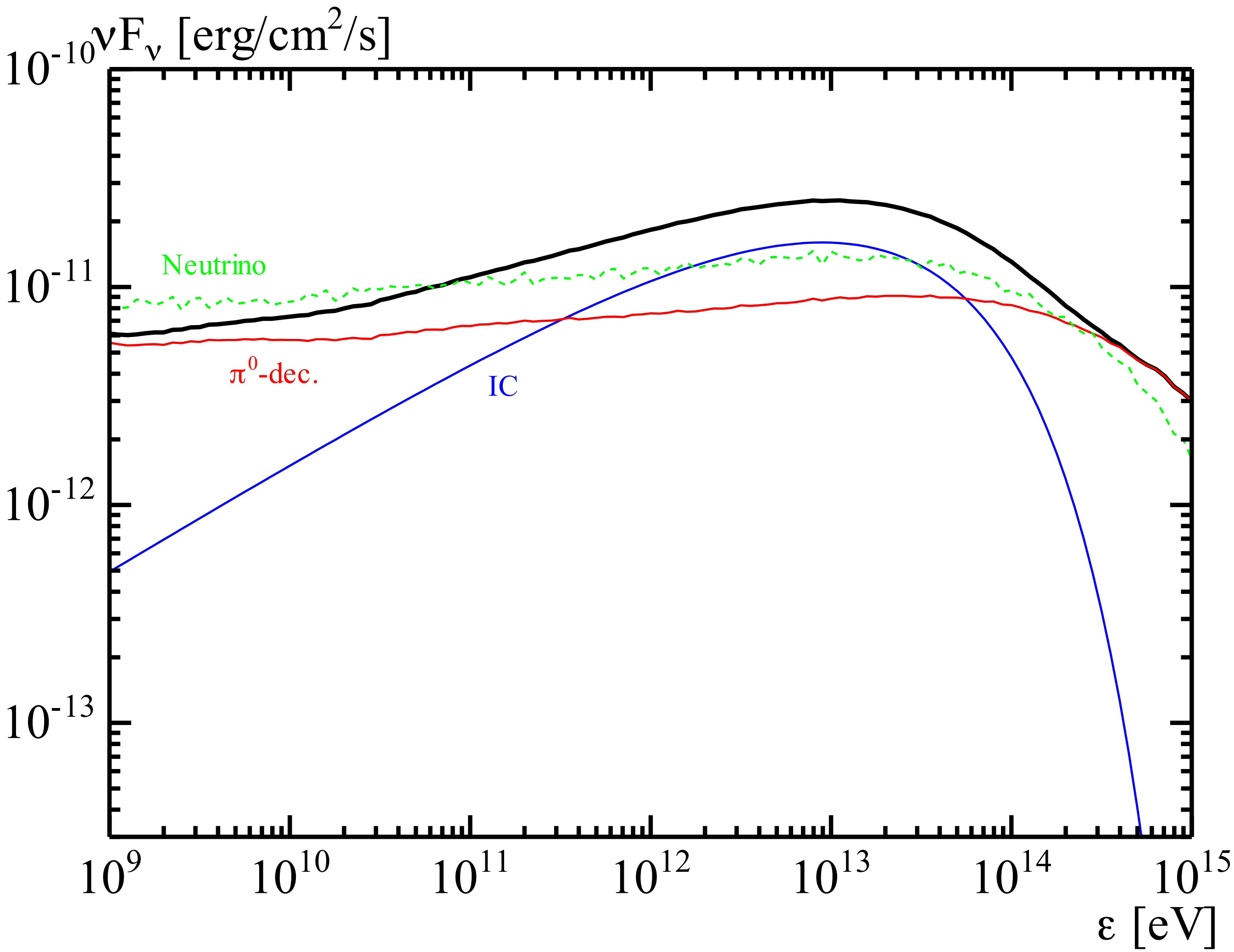
No significant clustering of the events

Candidate sources → ***starbursts ?***

(extragalactic, many sources, Emax~$10^{15\text{-}17}$ eV?)

(see also Murase+13 PRD, Chang & Wang 14 ApJ, Tamborra+14 JCAP)

Neutrino emission



test calc.
by Asano
(ICRR)

ν~1.44 γ
(π^0-dec)

contribution of SB galaxies (with Asano-san)

Observational results by Fermi : $\log(L_{0.1-100\,\mathrm{GeV}}/L_{8-1000\,\mu\mathrm{m}}) = -4.3$

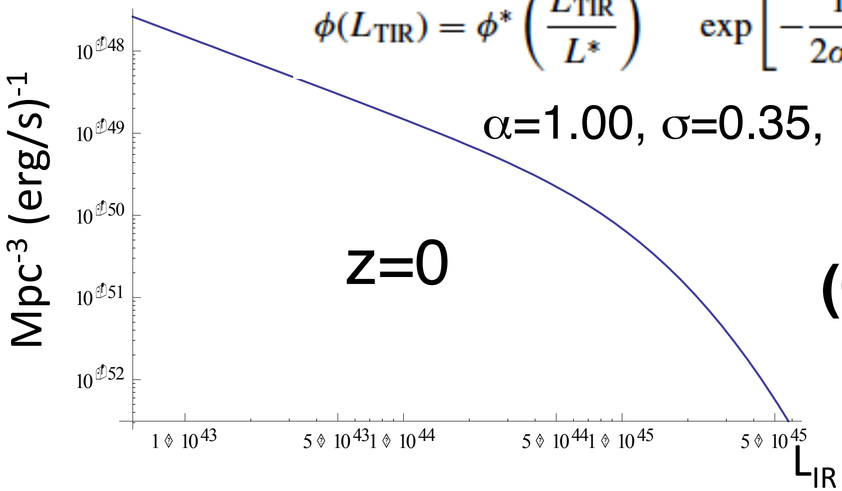
Γ=2.2 ⇨ $\int_{0.1\mathrm{GeV}}^{100\mathrm{GeV}} L_{0.1}\left(\frac{\varepsilon}{0.1\mathrm{GeV}}\right)^{-1.2} d\varepsilon = 10^{-4.3} L_{\mathrm{IR}}$ ⇨ **$(0.1\mathrm{GeV})L_{0.1}=1.34\times10^{-5}L_{\mathrm{IR}}$**

Infrared Luminosity Function (Gruppioni+13)

$$\phi(L_{\mathrm{TIR}}) = \phi^* \left(\frac{L_{\mathrm{TIR}}}{L^*}\right)^{1-\alpha} \exp\left[-\frac{1}{2\sigma^2}\log_{10}^2\left(1+\frac{L_{\mathrm{TIR}}}{L^*}\right)\right]$$

⇨ (>0.01 L^*) 1.9×10^{40} erg/s/Mpc^3

α=1.00, σ=0.35, $L^*=10^{11.17}L_{\mathrm{sun}}$



$(0.1\mathrm{GeV})L_{0.1}/\mathrm{Mpc}^3=2.56\times10^{-5}$ erg/s/Mpc^3

Converted to ν : $\frac{(\mathrm{PeV})L_{\mathrm{PeV}}}{\mathrm{Mpc}^3} \sim 1.44\times\left(\frac{\mathrm{PeV}}{0.1\mathrm{GeV}}\right)^{-0.2}\frac{(0.1\mathrm{GeV})L_{0.1}}{\mathrm{Mpc}^3} \sim 1.47\times10^{34}$ erg/s/Mpc^3

$$\dot{n}_\nu \sim 9.14\times10^{15}\left(\frac{\varepsilon_\nu}{\mathrm{PeV}}\right)^{-2.2} \mathrm{s}^{-1}\,\mathrm{eV}^{-1}\,\mathrm{Mpc}^{-3}$$

contribution of SB galaxies (with Asano-san)

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$$n_\nu(\varepsilon_\nu) = \int (1+z)\, \dot{n}_\nu((1+z)\varepsilon_\nu) \frac{dt}{dz} dz$$

$$\varepsilon_\nu I_\nu = c \frac{\varepsilon_\nu^2 n_\nu(\varepsilon_\nu)}{4\pi} \quad \text{(z<4)}$$

$\dot{n}_\nu$: constant

$$\varepsilon_\nu I_\nu = 1.59 \times 10^{-10}\ \mathrm{GeV\,sr^{-1}\,cm^{-2}\,s^{-1}}$$

$\dot{n}_\nu \propto (1+z)^3$

$$\varepsilon_\nu I_\nu = 1.10 \times 10^{-9}\ \mathrm{GeV\,sr^{-1}\,cm^{-2}\,s^{-1}}$$

$\dot{n}_\nu \propto (1+z)^6$

$$\varepsilon_\nu I_\nu = 3.58 \times 10^{-8}\ \mathrm{GeV\,sr^{-1}\,cm^{-2}\,s^{-1}}$$

too low if (1+z)^3
or very high evolution

IceCube:
E$^2\Phi$ (@PeV) ~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

if neutrino index = 2

$$\frac{(\mathrm{PeV})L_{\mathrm{PeV}}}{\mathrm{Mpc}^3} \sim 1.44 \times \frac{(0.1\mathrm{GeV})L_{0.1}}{\mathrm{Mpc}^3}$$

$$\sim 3.68 \times 10^{35}\ \mathrm{erg/s/Mpc^3}$$

$$\dot{n}_\nu \sim 2.30 \times 10^{17} \left(\frac{\varepsilon_\nu}{\mathrm{PeV}}\right)^{-2.0} \mathrm{s^{-1}\,eV^{-1}\,Mpc^{-3}}$$

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if neutrino index = 2

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$$\sim 3.68\times10^{35}\ \mathrm{erg/s/Mpc^3}$$

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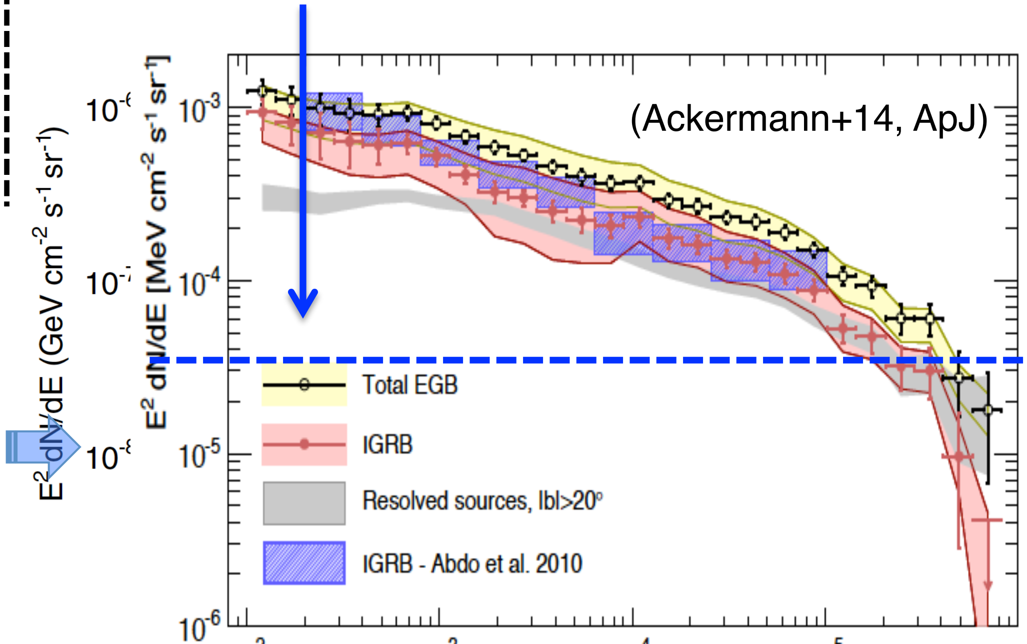
$\dot{n}_\nu \propto (1+z)^3$

$$\varepsilon_\nu I_\nu = 3.34\times10^{-8}\ \mathrm{GeV\,sr^{-1}\,cm^{-2}\,s^{-1}}$$



Summary

- Starbursts have been established as γ-ray source among radio-quiet galaxies
  - globally: Γ~2.2, following L_γ vs. L_{IR} (vs. L_{radio}) correlation
- The origin of γ-ray emission is likely to originate from cosmic rays interacting with ISM
- One expectation: Circinus galaxy
  - shows higher γ-ray luminosity than expected from CR origin
  - but, the emission origin is not clear, yet
- CTA helps to understand the γ-ray origin and cosmic-ray properties
  - detailed γ-ray spectral shape (cut off?)
  - Highest energy CRs in starburst systems?
  - PeV neutrino origin???